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Nucleation and Annihilation of Magnetic Vortices in Sub-Micron Permalloy Dots

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***Abstract*—The magnetization reversal processes in $Fe_{20}Ni_{80}$ dot arrays have been studied both experimentally and theoretically. The circular-shaped dots with thickness of 60 nm and variable diameters of 0.2–0.8 μm were fabricated by using electron-beam lithography and lift-off technique. A size dependent vortex nucleation, annihilation and initial susceptibility were determined from magneto-optical hysteresis loops. With increasing dot diameter the nucleation and annihilation fields decrease, whereas the initial susceptibility exhibits a linear increase. The experimental data were compared to the results of analytical calculations taking into account magnetostatic interactions, exchange and Zeeman energies for a planar array of magnetically soft circular dots.**

***Index Terms*—Circular dots, magnetic vortex, permalloy, vortex nucleation and annihilation.**

I. INTRODUCTION

MAGNETIZATION reversal in small magnetic systems is a subject of scientific interest as well as technological importance. In such systems, the relevant length scale is the exchange length, which is comparable to the domain wall width. When the dimensions of a patterned element are larger than the exchange length, magnetic vortices can be developed in the remanent state. For example, in the absence of an external magnetic field, an isolated polycrystalline disk exhibits a single-domain ("flower" or nearly uniform) magnetization state when the disk radius R is below the critical value R_{cr} for a given thickness L, whereas a vortex-type state appears above R_{cr} [1]. Such a magnetic vortex state has recently been observed experimentally [1]–[5]. Lorenz electron microcopy was used to study field-dependent vortex evolution in rectangular-shaped permalloy particle [2]. The correlation between vortex nucleation/annihilation fields and the demagnetizing factors has been studied for ellipsoidal cobalt dots [3]. Interesting magnetic force microscope (MFM) observation of the magnetic vortex states under an applied field is described in [4]. The vortex nucleation and annihilation in magnetic random access memory (MRAM) cells has also been observed [5].

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In the present work, we have studied the characteristic size dependent parameters of magnetization reversal in $Fe_{20}Ni_{80}$ dot arrays, such as vortex nucleation H_n and annihilation H_{an} fields, and initial susceptibility $\chi(0)$. The results of analytical calculations for H_n, H_{an}, and $\chi(0)$ taking into account the magnetostatic, exchange and Zeeman energy terms are compared with the obtained experimental data.

II. EXPERIMENTAL

A. Sample Fabrication

The samples were fabricated by means of high-resolution e-beam (EB) lithography and lift-off technique as follows. First, a silicon wafer substrate was spin-coated with two resist layers of positive type (PMGI and ZEP520). After pre-baking, the desired pattern was drawn with an EB lithographer (JEOL 5000SD), followed by resist development. Then $Fe_{20}Ni_{80}$ film was deposited by the EB evaporator at room temperature. The deposition ratio for all samples was $\sim$1 Å/s, resulting in a film with fine polycrystalline structure. The as-deposited reference film shows a coercive field of about 2 Oe. Finally the arrays of circular dots were obtained after an ultrasonic assisted lift-off process. The dots height is typically 60 nm and diameters are 0.2 μm, 0.4 μm, 0.6 μm and 0.8 μm. The dots are arranged in square lattices with an inter-dot spacing equal or bigger than the dot diameter.

B. Measurements

The geometry of the dots was examined by a scanning electron microscope (SEM) and an atomic force microscope (AFM). The magnetic vortex state in remanence was observed with MFM. The hysteresis loops were measured with magneto-optical Kerr effect over large areas of dot arrays (0.5 mm x 0.5 mm) in longitudinal geometry. The real and imaginary parts of the susceptibility were measured with a physical property measurement system (PPMS6000) with an AC field of 10 Oe at frequencies ranging from 10 Hz to 10 kHz. All measurements were performed at room temperature.

III. THEORETICAL DESCRIPTION

The first realistic magnetization curling mode ("vortex") in a flat circular cylindrical dot was considered by Aharoni [6]. The remanent magnetization distribution in cylindrical coordinates (oz axis is the cylinder axis, ϑ, φ are the polar and azimuthal angles, respectively) is described as follows:

$$m_\rho = 0; \quad m_\varphi = f(\rho); \quad m_z = \sqrt{1 - m_\varphi^2}. \qquad (1)$$

Usov *et al.* [7], using the substitution $f(\rho) = \sin\vartheta(\rho)$, have found from a variational procedure that $tg\vartheta/2 = \rho/b$, where b is the radius of the vortex core. The unit magnetization vector $\mathbf{m}$ deviates from the dot's plane for $\rho < b$. The value of b can be determined by minimizing the total particle's energy.

We assume here that the magnetization distribution under an applied external magnetic field can be described as a "shifted vortex," i.e., the vortex moves perpendicularly to the field while keeping its shape. Using this assumption, and (1) one can express the total magnetic energy of the dot (W), composed of exchange, magnetostatic, and Zeeman terms as a function of the vortex core displacement l divided by the dot radius R as follows [8]:

$$w(s) = \frac{W(s)}{M_s^2 V} = w(0) + a(\beta, R)s^2 - \frac{H}{M_s}s + O(s^4),$$
$$a(\beta, R) = 2\pi F_1(\beta) - \frac{1}{2}\left(\frac{\xi_0}{R}\right)^2,$$
$$F_\mu(\beta) = \int_0^\infty \frac{dt}{t} f(\beta t) J_\mu^2(t), \tag{2}$$

where

s $= l/R$,
β $= L/R$,
V is the dot volume,
ξ_0 is the exchange length,
$J_\mu(t)$ is the Bessel's function,
μ is an integer, and
$f(x)$ $= 1 - (1 - \exp(-x))/x$.

$F_1(\beta)$ is proportional to the average dot in-plane demagnetization factor [9].

The equilibrium position of the vortex as a function of the dot size and the external field can be found by minimizing the total magnetic energy (2). This immediately leads to an expression for the initial susceptibility $\chi(0)$ of an isolated cylindrical dot for in-plane magnetic field:

$$\chi(0) = \frac{1}{2a(\beta, R)}. \tag{3}$$

To find the vortex nucleation field, we consider the stability of the uniformly magnetized state with decreasing external magnetic field. The dot nucleation problem is complicated due to the nonellipsoidal dot shape. We assume here an initial magnetization curling with its center outside the dot at a distance $l_0 = R/\sin\varphi_0$ from the dot center, parameterized by the angle φ_0. Considering the first and second derivatives of the total magnetic energy decomposition in series of $\varphi_0$one can obtain the critical field, below which a uniform magnetic state ($\varphi_0 = 0$) is not stable. This field has the meaning of a vortex nucleation field:

$$H_n(\beta, R) = 4\pi M_s \left(F_1(\beta) - F_2(\beta) - \frac{1}{\pi}\left(\frac{\xi_0}{R}\right)^2\right). \tag{4}$$

Finally, the vortex annihilation field H_{an}, can be estimated as a first approximation by putting $s = 1$. This satisfies the condition when the center of the vortex crosses the dot boundary and gives:

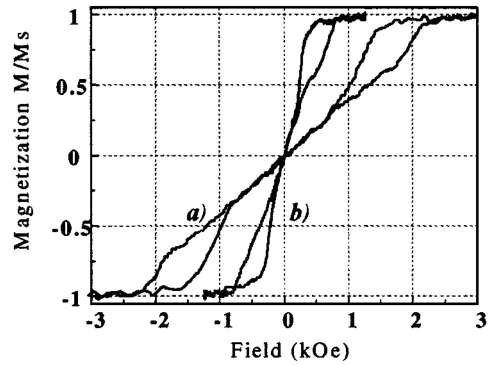

Fig. 1. The magneto-optical hysteresis loops measured for the 60 nm thick dots with diameters (a) 0.2 μm and (b) 0.8 μm.

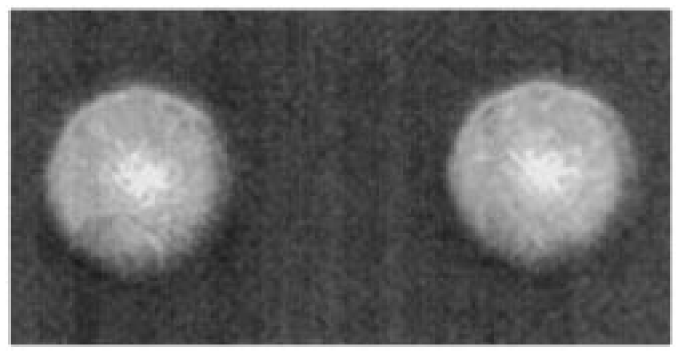

Fig. 2. MFM image taken in remanent state for 0.8 μm dots. The bright contrast spots are due to an out of plane magnetization component at the vortex core.

$$H_{an}(\beta, R)|_{s\approx 1,} = 2M_s a(\beta, R). \tag{5}$$

The magnetostatic and exchange contributions to the vortex annihilation field (5) are competitive.

IV. Results and Discussion

Fig. 1 compares the magneto-optical hysteresis loops measured for two kinds of dot arrays with the same thickness and different diameters 0.2 μm and 0.8 μm. When the magnetic field is decreased from saturation, a magnetic vortex nucleates at the nucleation field H_n from the edge of the dot accompanied by an abrupt decrease in magnetization. This results in a magnetostatic energy gain. Fig. 2 shows typical MFM image confirming the vortex spin structure of the dots in remanence. The reversible linear part of the loop corresponds to the vortex core movement perpendicular to the applied field. Next, when the magnetic field reaches the annihilation field H_{an} the vortex vanishes completely and the dot stabilizes in the single-domain state. The values H_n, H_{an} and the slope of the linear part of hysteresis loop are strongly size-dependent. Initial susceptibility $\chi(0)$ increases linearly from 0.3 to 1.3 for the dot arrays with diameters 0.2 μm and 0.8 μm, respectively. The measurements of real and imaginary parts of the susceptibility with an AC field of 10 Oe show that the vortex displacement is frequency-independent, at least in the range 10 Hz–10 kHz.

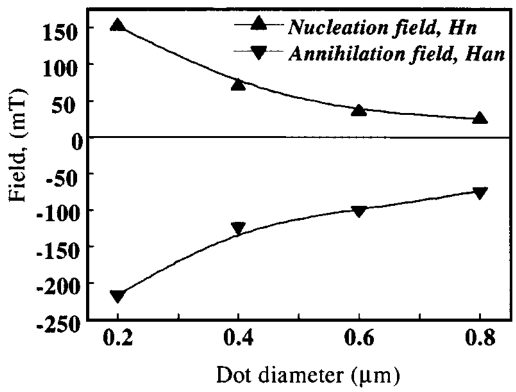

Fig. 3. The experimental data for the nucleation and annihilation fields obtained from hysteresis loops.

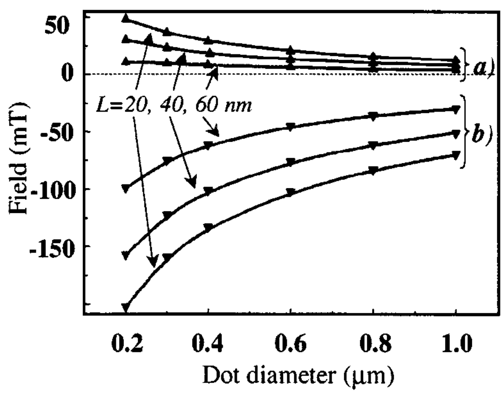

Fig. 4. The nucleation (a) and annihilation (b) fields calculated from (4) and (5).

Fig. 2 summarizes the experimental data for H_n and H_{an}. For the dot arrays with the small diameter the vortex nucleation happened in quite strong field, and the strong magnetic field is required to magnetize the dot uniformly. Therefore, magnetization reversal due to the vortex nucleation/annihilation appear to be not desirable in MRAM memory elements [5]. As the dot diameter increases, both the nucleation and annihilation fields decrease. The vortex nucleation field is always smaller then annihilation field for all the samples investigated.

Equations (3)–(5) describe analytically the characteristic parameters of the magnetization reversal in individual polycrystalline circular dots by using only the geometry of the dot (L and R) and the saturation magnetization M_s. The exchange contribution (ξ_0 is about 18 nm for FeNi) influences H_n, H_{an} slightly for the R values investigated. This means that the fields are determined by in-dot magnetostatic interaction and depend only on the dot aspect ratio β. The same scaling relationship of the critical fields was measured in [3] for polycrystalline sub-micron size elliptical Co dots. The size-dependent nucleation field H_n and annihilation field H_{an} obtained from (4) and (5) are plotted in Fig. 3. The calculated results correlate well with the experimental data. The increase of the nucleation and annihilation fields with decreasing the dot sizes (R, L), as measured for the circular FeNi dot arrays, is related to demagnetizing fields of the dot. The initial susceptibility $\chi(0)$ as calculated by using (3) agree qualitatively with experimental data, indicating that thinner circular dots with larger diameters yield a higher mobility of the vortex core under the influence of an applied magnetic filed. In our experiments, the dot array period is larger than the dot diameter allowing to neglect the interdot magnetostatic interaction. However, the situation is quite different if the period of the dot array becomes comparable to the dot diameter. In particular, by using the approach developed in [10], we have found that the magnetostatic coupling leads to a significant decrease of H_n, H_{an}, and an increase in $\chi(0)$.

V. Conclusion

In summary, size-dependent vortex nucleation, and annihilation fields as well as the initial susceptibility have been studied experimentally and theoretically for circular polycrystalline FeNi dots. With increasing dot diameter both the nucleation and annihilation fields decrease, whereas the initial susceptibility exhibits a linear increase. Simple analytical approximations are suggested to describe the zero field susceptibility, and the nucleation and annihilation fields. The calculated results agree well with the experimental data within the limit of weak inter-dot coupling. Further studies of static and dynamic properties of the magnetization reversal in isolated and magnetostatically coupled dots are in progress.

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